

# GROUPS OF GALAXIES IN THE LAS CAMPANAS REDSHIFT SURVEY

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## Abstract

A “friends-of-friends” percolation algorithm has been used to extract a catalogue of  $\delta\rho/\rho = 80$  density enhancements (groups) from the six slices of the Las Campanas Redshift Survey (LCRS). The full catalogue contains 1495 groups and includes 35% of the LCRS galaxy sample. A statistical sample of 394 groups has been derived by culling groups from the full sample which either are too close to a slice edge, have a crossing time greater than a Hubble time, have a corrected velocity dispersion of zero or less, or contain a 55 arcsec “orphan” (a galaxy with a “faked” redshift excluded from the original LCRS redshift catalogue due to its proximity — i.e., within 55 arcsec — of another galaxy). Median properties derived from the statistical sample include: line-of-sight velocity dispersion  $\sigma_{\text{los}} = 164 \text{ km s}^{-1}$ , crossing time  $t_{\text{cr}} = 0.10 H_0^{-1}$ , harmonic radius  $R_{\text{h}} = 0.58 h^{-1} \text{ Mpc}$ , pairwise separation  $R_{\text{p}} = 0.64 h^{-1} \text{ Mpc}$ , virial mass  $M_{\text{vir}} = 1.90 \times 10^{13} h^{-1} M_{\text{sun}}$ , total group  $R$ -band luminosity  $L_{\text{tot}} = 1.40 \times 10^{11} h^{-2} L_{\text{sun}}$ , and  $R$ -band mass-to-light ratio  $M/L = 153 h M_{\text{sun}}/L_{\text{sun}}$ .

# 1 The Las Campanas Redshift Survey (LCRS)

The Las Campanas Redshift Survey (LCRS; Shectman et al. 1996) is an optically selected galaxy redshift survey which extends to a redshift of 0.2 and which is composed of a total of 6 alternating  $1.5^\circ \times 80^\circ$  slices, 3 each in the North and South Galactic Caps. Now completed, the LCRS contains 26,418 galaxy redshifts, of which 23,697 lie within the official geometric and photometric limits of the survey. Accurate  $R$ -band photometry and sky positions for program objects were extracted from CCD drift scans obtained on the Las Campanas Swope 1-m telescope; spectroscopy was performed at the Las Campanas Du Pont 2.5-m telescope, originally via a 50-fiber Multi-Object Spectrograph (MOS), and later via a 112-fiber MOS. For observing efficiency, all the fibers were used, but each MOS field was observed only once. Hence, the LCRS is a collection of 50-fiber fields (with nominal apparent magnitude limits of  $16.0 \leq R < 17.3$ ) and 112-fiber fields (with nominal apparent magnitude limits of  $15.0 \leq R < 17.7$ ); see **Figure 1**. Thus, selection criteria vary from field to field, but these selection criteria are carefully documented and therefore easily taken into account. Observing each field only once, however, created an additional selection effect: the protective tubing of the individual fibers prevented the spectroscopic observation of both members of galaxy pairs within 55 arcsec of each other. Hence, groups and clusters can be undersampled, potentially causing physical groups to be split by a “friends-of-friends” percolation algorithm and resulting in the mis-estimate of general group properties. We will return to this problem in the next section.

## 2 Extracting The Group Catalogue

In constructing the LCRS Group Catalogue, we have considered only those LCRS galaxies within the official geometric and photometric borders of the survey; we have furthermore limited this sample to galaxies having redshifts in the range

$$7,500 \text{ km s}^{-1} \leq cz_{\text{cmb}} < 50,000 \text{ km s}^{-1} \quad (1)$$

and luminosities in the range

$$-22.5 \leq M_R - 5 \log h < 17.5 \quad (2)$$

(see **Figure 2**).

Moreover, each of the  $\sim 1,000$  galaxies which were excluded from LCRS redshift catalogue due to the fiber-separation effect has been re-introduced into the sample by assigning it a redshift equal to the redshift of its nearest neighbor convolved with a gaussian of width  $\sigma = 200 \text{ km s}^{-1}$  (roughly the mean line-of-sight velocity dispersion of a cleaned LCRS group sample which excludes these 55-arcsec “orphans”). The re-included galaxies subscribe to all the same limits imposed upon the original sample.

The group catalogue was extracted using a standard “friends-of-friends” percolation algorithm (Huchra & Geller 1982) modified for comoving distances and for field-to-field sampling variations. To take into account the latter, the projected separation and velocity difference linking parameters,  $D_L$  and  $V_L$ , respectively, were scaled according to the following equations (which assure that the ratio  $D_L/V_L$  is independent of environment):

$$D_L = D_0 \times S_L \quad \text{and} \quad V_L = V_0 \times S_L, \quad (3)$$

where  $D_0$  and  $V_0$  are  $D_L$  and  $V_L$ , respectively, for a given fiducial field at at given fiducial redshift, and where  $S_L$  is a linking scale which takes into account variations in galaxy sampling rate. It is defined by

$$S_L \equiv \left[ \frac{\rho^{\text{exp}}(f, z)}{\rho_{\text{fid}}^{\text{exp}}} \right]^{-1/3} \quad (4)$$

where  $\rho^{\text{exp}}(f, z)$  is the number density of galaxies one would expect to observe at redshift  $z$  in field  $f$  for a homogeneous sample having the same selection function and sampling fraction as the LCRS redshift catalogue;  $\rho_{\text{fid}}^{\text{exp}}$  is  $\rho^{\text{exp}}(f, z)$  for a given fiducial field at a given fiducial redshift. Due to the simple field characteristics, we have chosen the fiducial field to have 100% sampling, flux limits of  $15.0 \leq R < 17.7$ , and the same luminosity function as the LCRS Northern 112-fiber sample (Lin et al. 1996); since it is roughly the median redshift of the survey, we have chosen the fiducial redshift  $cz_{\text{fid}}$  to be  $30,000 \text{ km s}^{-1}$ .

Finally, to avoid group-member incompleteness at the extremal distances of the sample, only groups within

$$10,000 \text{ km s}^{-1} \leq cz_{\text{cmb}} < 45,000 \text{ km s}^{-1} \quad (5)$$

were admitted into the final group catalogue.

### 3 Properties of LCRS Groups

The full catalogue contains 1495 groups and includes 35% of the LCRS galaxy sample (**Figures 3** and **4**). A statistical sample of 394 groups was extracted from the full sample by culling groups which either were too close to a slice edge, had a crossing time greater than a Hubble time, had a corrected velocity dispersion of zero or less, or contained a 55 arcsec “orphan”. Some of the characteristics of the statistical sample are listed in **Table I**, including medians of the following group properties:

- The group line-of-sight velocity dispersion,  $\sigma_{\text{los}}$ , corrected for relativistic effects (Harrison 1974) and for estimated random errors in the LCRS redshifts.
- The mean pairwise separation,

$$R_p = \frac{8D_{\text{grp}}}{\pi} \sin \left\{ \frac{1}{2} \left[ \frac{\sum_i \sum_{j>i} w_i w_j \theta_{ij}}{\sum_i \sum_{j>i} w_i w_j} \right] \right\}, \quad (6)$$

where  $D_{\text{grp}}$  is the comoving distance to the group,  $\theta_{ij}$  is the angular separation between group members  $i$  and  $j$ , and  $w_i$  and  $w_j$  are the respective weights for  $i$  and  $j$ ,

$$w_i \equiv [\rho^{\text{exp}}(f_i, z_i)]^{-1} \quad (7)$$

This weighting factor helps to counteract a bias resulting from a group straddling two fields with different galaxy sampling characteristics.

- The harmonic radius,

$$R_h = \pi D_{\text{grp}} \sin \left\{ \frac{1}{2} \left[ \frac{\sum_i \sum_{j>i} w_i w_j \theta_{ij}^{-1}}{\sum_i \sum_{j>i} w_i w_j} \right]^{-1} \right\}. \quad (8)$$

- The crossing time for the group,

$$t_{\text{cr}} = \frac{3}{5^{3/2}} \frac{R_h}{\sigma_{\text{los}}}, \quad (9)$$

in units of the Hubble time ( $H_0^{-1}$ ).

- The group’s virial mass,

$$M_{\text{vir}} = \frac{6\sigma_{\text{los}}^2 R_h}{G}, \quad (10)$$

where  $G$  is the gravitational constant.

- The total group luminosity in the LCRS  $R$ -band,  $L_{\text{tot}}$ , corrected via the selection function to account for galaxies not observed by the LCRS.
- The group mass-to-light ratio in the LCRS  $R$ -band,  $M/L$ .

The above definitions are very similar to those used by Ramella, Geller, & Huchra (1989), but modified to take into account cosmological effects (due to the LCRS sample depth) and field-to-field sampling variations.

**Table I** lists the properties of LCRS groups from the whole statistical sample, of those groups from just the 50-fiber fields, of those groups from just the 112-fiber fields, and of those groups which straddle the border of a 50-fiber and a 112-fiber field; also tabulated are the general properties from an earlier incarnation of the LCRS  $\delta = -6^\circ$  group catalogue [Tucker 1994 (T94)]. The 50-fiber-field groups appear to be typically a little larger than the 112-fiber-field groups in both projected size ( $\langle R_p \rangle_{\text{med}}$  &  $\langle R_h \rangle_{\text{med}}$ ) and velocity extent ( $\langle \sigma_{\text{los}} \rangle_{\text{med}}$ ), indicating that the *effective* linking scale for the 50-fiber fields may be systematically larger than that for the 112-fiber fields, in spite of efforts to avoid such a bias. On the other hand, much of the apparent divergence of the 50/112 group properties can be attributed to this sample’s aberrantly high median velocity dispersion (e.g., recall  $M_{\text{vir}} \propto \sigma_{\text{los}}^2$ ), which in turn may be due to the small size of the 50/112 statistical sample or to the difficulties of properly extracting groups which straddle the border between a 50-fiber and a 112-fiber field.

Finally, for comparison, we have also listed in **Table I** the median group properties from several other group catalogues. These include those based upon the the original CfA redshift survey [CfA1; Nolthenius & White 1987 (NW87); Nolthenius 1993 (N93); Moore, Frenk, & White 1993 (MFW93)], the Southern Sky Redshift Survey [SSRS; Maia, da Costa, & Latham 1989 (MdCL89)], and the CfA extension to  $m_{\text{B}(0)} = 15.5$  [CfA2; Ramella, Geller, & Huchra 1989 (RGH89); Ramella, Pisani, & Geller 1997 (RPG97)].

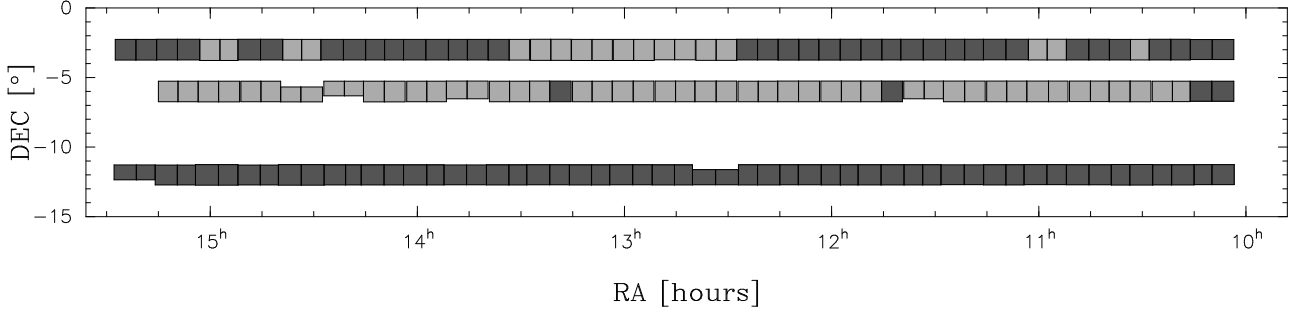
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## Acknowledgments

This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

The LCRS Survey Pattern: The North Galactic Cap Region



The LCRS Survey Pattern: The South Galactic Cap Region

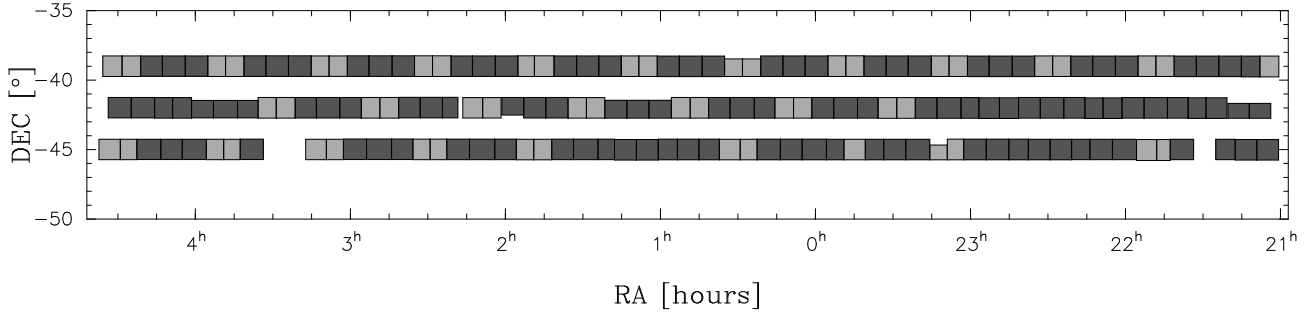


Figure 1: The LCRS survey pattern for the Northern (top) and the Southern (bottom) Galactic Cap regions. Lightly shaded regions denote fields observed with the 50-fiber MOS and darkly shaded regions fields observed with the 112-fiber MOS. Declination and right ascension coordinates are epoch 1950.0

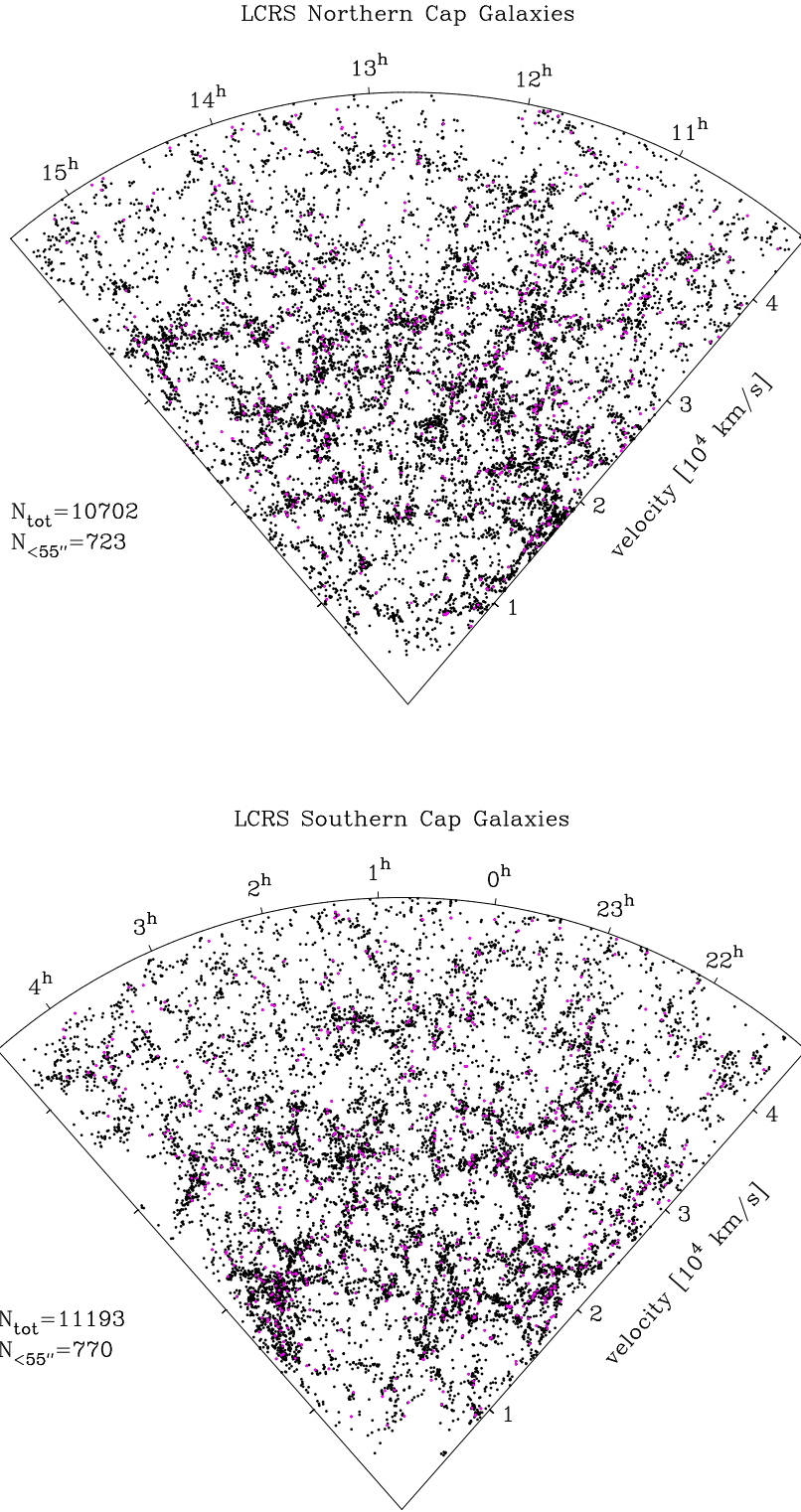


Figure 2: The distribution of galaxies in the LCRS Northern (top) and Southern (bottom) Galactics out to  $cz = 46,000$  km s<sup>-1</sup>. Only those galaxies having luminosity  $-22.5 \leq M_R - 5 \log h < -17.5$  and lying within the LCRS official geometric and photometric boundaries are plotted. Red points are the 55-arcsec “orphans,” plotted with their “faked” velocities.  $N_{\text{tot}}$  is the total number of galaxies plotted, 55-arcsec “orphans” included;  $N_{<55''}$  refers to the number of 55-arcsec “orphans” plotted.



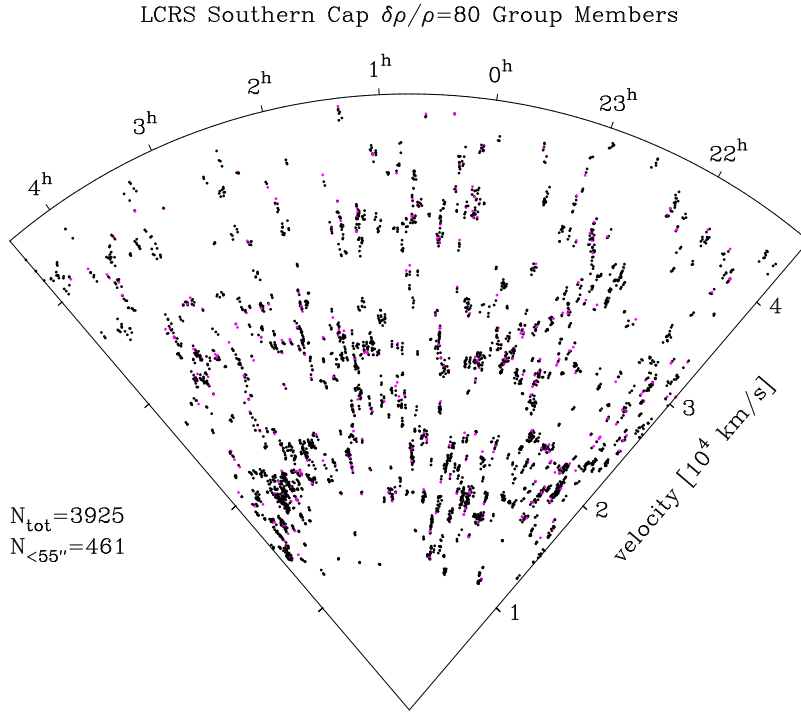
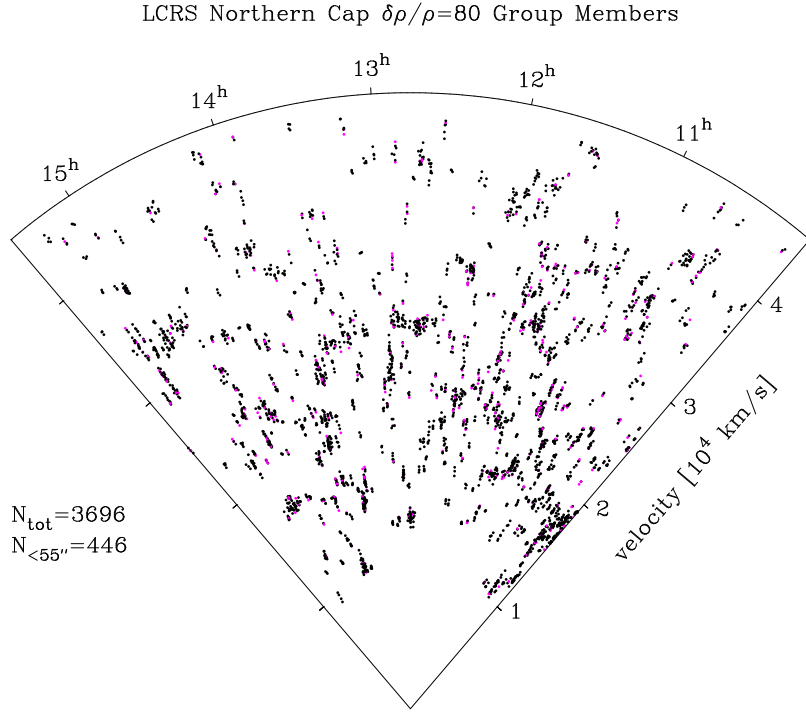


Figure 3: Same as Figure 1, but only galaxies in  $\delta\rho/\rho = 80$  groups are plotted.

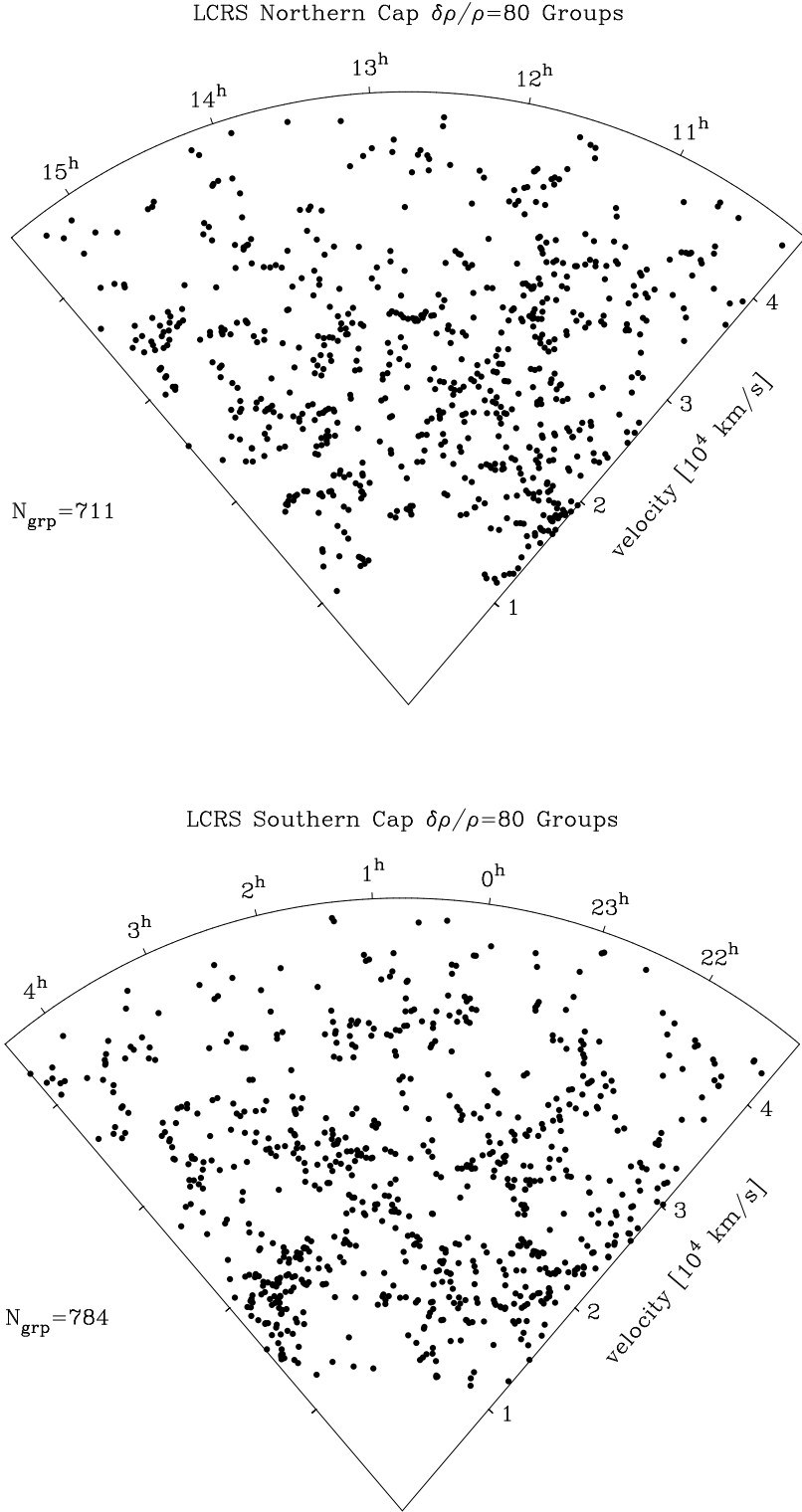


Figure 4: The distribution of  $\delta\rho/\rho = 80$  groups in the LCRS Northern (top) and Southern (bottom) Galactic Caps. The LCRS Group Catalogue extends from  $cz = 10,000 \text{ km s}^{-1}$  to  $cz = 45,000 \text{ km s}^{-1}$ ; so the dearth of groups at  $cz < 10,000 \text{ km s}^{-1}$  is not physical but merely the cutoff of the catalogue.

TABLE I  
COMPARISON OF GROUP CATALOGUES\*

	LCRS					CfA1			SSRS	CfA2		
	All	50	112	50/112	T94	NW87	N93	MFW93	MdCL89	RGH89 (all)	RGH89 (rich) <sup>†</sup>	RPG97
% of galaxies in groups	35%	30%	37%	...	23%	61%	48%	55%	35%	44%	13%	42%
# of groups in catalogue	1495	274	1193	28	114	166	173	166	87	128	56	406
# of groups in statistical sample	394	79	310	5	52	166	173	166	87	52	36	406
$\langle \sigma_{\text{los}} \rangle_{\text{med}} [\text{km s}^{-1}]$	164	211	150	286	177	123	116	155	183	209	228	192
$\langle H_0 t_{\text{cr}} \rangle_{\text{med}}$	0.10	0.09	0.11	0.09	0.13	0.13	0.10	0.10	0.06	0.06	0.06	0.054
$\langle R_h \rangle_{\text{med}} [h^{-1} \text{ Mpc}]$	0.58	0.75	0.55	0.71	0.75	0.67	0.48	...	0.48	0.51	0.52	0.43
$\langle R_p \rangle_{\text{med}} [h^{-1} \text{ Mpc}]$	0.64	0.83	0.60	0.68	0.84	1.13	0.72	...	0.53	0.67	0.69	...
$\langle M_{\text{vir}} \rangle_{\text{med}} [10^{13} h^{-1} M_{\odot}]$	1.90	4.00	1.60	11.00	2.50	1.55	...	...	1.62	2.00	3.89	1.86
$\langle L_{\text{tot}} \rangle_{\text{med}} [10^{11} h^{-2} L_{\odot}]^{\ddagger}$	1.40	2.30	1.10	2.10	1.75	0.68	...	...	...	...	...	1.12
$\langle M/L \rangle_{\text{med}} [h M_{\odot}/L_{\odot}]^{\ddagger}$	153	162	148	418	182	264	148	298	...	186	175	240

\*Values for the non-LCRS group catalogues were taken from the original papers. Where necessary, values were converted to be consistent with the definitions associated with the LCRS group properties.

<sup>†</sup>RGH89 rich groups are those containing 5 or more members.

<sup>‡</sup>Luminosities for the LCRS group catalogues are in the  $R_{\text{G;K-G}}$ -band; for the various CfA1 and CfA2 group catalogues, in the de Vaucouleurs  $B(0)$ -band. A rough conversion is  $L_R \sim 1.1 L_{B(0)}$  ( $M/L_{B(0)} \sim 1.1 M/L_R$ ). The SRSS is a diameter-limited catalogue and contains no luminosity information.